Sustainable Cities and Society 44 (2019) 511–519

Contents lists available at ScienceDirect

Sustainable Cities and Society

journal homepage: www.elsevier.com/locate/scs

Implications of climate changes to building energy and design

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ARTICLE INFO

Keywords:
Climate change
Projection
Validation
Building stock
Energy use
Climate zone

ABSTRACT

Climate change is a widely acknowledged major environmental problem whose impacts on building energy use however are not fully understood. Various climate models have been developed and used to project climate changes; however most of existing studies on climate change impacts only use few model outcomes, providing narrow predictions on the influences. This study analyzed a large number (i.e., 56) of models and scenarios. The obtained future climate data showed a wider range of potential changes and thus impacts on building energy. Four reference climate models were identified to cover the full range of the 56 models for three time periods and seven climate zones. The accuracy of model projections was validated using historical data. The study predicted the potential energy implications of climate changes to a campus building stock. Influences of these changes on utility and economics were analyzed. The study further explored the potential impacts of climate change to the current climate zones that directly relate to building energy consumption.

1. Introduction

Climate change is widely acknowledged a primary environmental problem facing the planet. The Intergovernmental Panel on Climate Change (IPCC) estimated that between 1970 and 2004, global greenhouse gas emissions rose 70% (IPCC, 2007). Many of the effects of the building sector on climate change are well explored. The building sector contributes up to 30% of global annual greenhouse gas emissions and consumes up to 40% of all energy (IPCC, 2007). Furthermore, between 1971 and 2004, carbon emission is estimated to have grown at a rate of 2.5% per year for commercial buildings and at 1.7% per year for residential buildings (Levine, Urge-Vorsatz, Blok, Geng, Harvey, & Lang 2007). However, many of the potential effects of climate change on the building sector are not well studied. Changes in climate will have significant impacts on built environments and thus their designs and operations, and hence it will be crucial to understand these effects.

A few methods exist to analyze implications of climate change to building energy use. In early studies, a simple degree day based method was used (Amato, Ruth, Kirshen, & Jorwitz, 2005; Olonscheck, Holsten, & Kropp, 2011; Rosenthal, Gruenspecht, & Moran, 1995). The main principle of this method is that the building energy use is proportional to the heating and cooling degree hours for the location of the building. This method can provide an estimate of the impact of climate change (if future outdoor temperature is used) on buildings. However, this approach only accounts for sensible load because merely the dry bulb temperature (dbt) is taken into consideration. Solar radiation, humidity and other building characteristics are not considered.

Detailed hour by hour building energy simulation tools were recently used to study the impacts of climate change on building energy use (Chan, 2011; Cooper, 2010; Wang & Chen, 2014; Wang, Chen, & Ren, 2010). Most of these studies used several climate models to predict the influences of climate changes on a few typical building models. For instance, Wang, Liu, and Brown, (2017) used the HadCM3 and CESM1 climate projection models to predict the impacts of climate change on energy consumption for a medium-size office building and tested a set of HVAC operation related mitigation measures to offset the influences. Cellura, Guarino, and Sonia Longo (2018) used a Global Circulation Model (GCM) data to model the energy implications to an office building in Southern Europe that shows the increase in air temperature in South EU up to 9 °C and the cooling energy cooling increase up to 120% in 2090. Spandagos and Ng (2017) predicted the climate change impacts on building cooling and heating energy in large Asian cities and concluded that switching to more efficient air-conditioning devices can offset much of the increases, while Hwang, Shih, Lin, and Huang (2018) concluded that thermal insulation is gaining more concern while climate change proceeds. Pérez-Andreu, Aparicio-Fernández, Martínez-Ibernón, and Vivancos (2018) predicted the impacts of climate change on heating and cooling energy demand in a residential building in a Mediterranean climate with two GCMs for 2050 and 2100. The study indicated that heating energy demand decreases significantly, and cooling energy demand increases. They also suggested thermal insulation and infiltration have the greatest effect on total energy demand.

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https://doi.org/10.1016/j.scs.2018.10.043
Received 25 June 2018; Received in revised form 24 October 2018; Accepted 28 October 2018
Available online 01 November 2018
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Jiang and O'Meara (2018) also explored a series of thermal features of commercial building systems to mitigate energy consumption in Florida due to global climate change. Aijazi and Brager (2018) presented an overview and a case study to demonstrate how climate change impacts on building can be simulated and will vary by building type and location. It is generally agreed that the climate change impact on energy demand is sensitive to building type and location. Huang and Gurney (2016a) predicted that the warehouse showed an increase of > 100% energy consumption at some summer hours while the secondary school building showed an increase of > 39% energy consumption in August. At climate zone scale, changes in annual energy consumption can range from −17% to +21%. Schuetter, Debaillie, and Ahl (2014) used energy modeling to investigate effects of future climate change on energy consumption, peak demand and energy costs at NASA's John C. Stennis Space Center in southern Mississippi. This was a rare example of predicting future climate change influence on a real building stock modeled using representative buildings. This study used only two future climate change sets provided by the North American Regional Climate Assessment Program (NARCCAP) – a high and low impact scenario. They found that the total annual projected energy was expected to increase 8.6% and 17.7% for the low and high scenarios.

More comprehensive studies were also found in literature. Shen (2017) integrated one GCM data to the typical meteorological year weather file to predict local hourly weather data in US using a morphing methodology. Case studies in four representative cities in the U.S. showed that the change of annual energy use is predicted to range from −1.64% to 14.07% for residential building and from −3.27% to −0.12% for office building under A2 scenario (a carbon emission scenarios defined by IPCC) in different regions in 2040–2069. The research suggested that the climate change will narrow the gap of energy use for residential buildings located in cold and hot climate regions in the U.S. and generally reduce office building energy use in the future. It was also found that the energy use of lightings and fans will slightly decrease in the future, but the growing peak electricity load during cooling seasons is going to exert greater pressure for the future grid. Rey-Hernández, Yousif, Gatt, Velasco-Gómez, José-Alonso, and Rey-Martínez (2018) modeled the long-term effect of climate change on a zero energy and carbon dioxide building through energy efficiency and renewable. Results showed that the cooling demand would significantly increase for the years 2050 and 2080, while space heating would drop. The previously excess generated electricity of the building by photovoltaics would then be totally consumed within the building due to increased demand, implying longer operation hours and thus more maintenance and replacement costs. Cao, Li, Wang, Xiong, and Meng (2017) investigated the effects of climate change on building energy-saving design in the different climate zones of China and found that the increasing rate of design temperatures for both heating and air-conditioning in winter were in the range of 0.2 °C – 0.7 °C/decade, and the rate of design temperature for air-conditioning in summer was in the range of 0.1 °C – 0.4 °C/decade. Angeles, González, and Ramírez (2018) assessed the impacts of climate change on building energy demands in the intra-Americas region using the Intergovernmental Panel on Climate Change (IPCC) Representative Concentration Pathways (RCP) 2.6 and 4.5 scenarios and forecasted an increase of 9.6 and 23 kW h/month, respectively by the end of the twenty-first century, which may increase average building cooling loads in the region by 7.57 GW (RCP2.6) and 8.15 GW (RCP4.5), respectively.

One a large scale, Gi, Sano, Hayashi, Tomoda, and Akimoto (2018) analyzed the global residential heating and cooling demands for different climate change scenarios up to 2050. They concluded that the space heating and cooling demand in 2050 in the world as a whole become 2.1–2.3 and 3.8–4.5 times higher than those for 2010, upon different global warming scenarios. Clarke, Eom, Marten, Horowitz, Kyle, and Link (2018) studied the effects of long-term climate change on global building energy expenditures and concluded that net expenditures decrease in some regions where heating demands currently dominate while net expenditures increase the most in areas with greater demand for space cooling. Reyna and Chester (2017) indicated that without policy intervention, residential electricity demand could increase by as much as 41–87% between 2020 and 2060. However, aggressive policies aimed at upgrading heating/cooling systems and appliances could result in electricity use increases as low as 28%, potentially avoiding the installation of new generation capacity. Huang and Gurney (2016b) suggested that the changes at the state/month scale that are much larger with summer electricity demand increases exceeding 50% and spring non-electric energy declines of 48% by the end of the century, while the US national/annual total source energy consumption differences between the 2080–2099 time period and the present are less than 2%. Huang and Gurney (2017) further estimated the financial implications of climate change on U.S. building energy demand. They estimated that building energy costs decrease by ~7 billion $/year in the residential sector, while increase by ~2.2 billion $/year in the commercial sector. For cold-weather states, there are residential energy savings of up to 340 $/year, while warmer states see increased residential energy costs of up to 231 $/year per household. The increased summertime cooling demand poses important questions for the electricity supply system. They also indicated that to maintain a reliable electricity supply requires an additional 80.6 GW (GW) of capacity.

The literature review reveals a wide range of predicted energy demand changes for buildings under projected future weathers due to different building types, locations, building models, and climate models used. Although general trends were observed as commonly sensed, some contradictive conclusions were presented. It indicates a need for a more comprehensive study that utilizes and analyzes a larger number of climate models and scenarios, as well as developing representative climate models that can cover a full range of possible future conditions. Most studies predate the IPCC Fifth Assessment Report (AR5) so the models and scenarios that were used have since been upgraded. The AR5 covers a larger range of scenarios than the Special Report on Emissions Scenarios (SRES) used in previous assessments (IPCC, 2014). When comparing the AR5 scenarios to the previous SRES scenarios, 3 of the 4 have an equivalent scenario. However, the stringent mitigation scenario has no equivalent, therefore there will be a difference in magnitude of the SRES and AR5 climate projections due to a wider range of emissions scenarios (IPCC, 2014). Using a large number of AR5 projections will allow a better estimate on the range of how climate change may affect a particular building or building stock.

2. Climate models

2.1. Overview

Climate models have been developed and used to project climate changes, upon a standard set of greenhouse gas scenarios called Representative Concentration Pathways (RCPs) used in the IPCC Fifth Assessment Report (AR5). RCPs describe four different 21st century pathways of greenhouse gas (GHG) emissions and atmospheric concentrations, air pollution and land use. They include a stringent mitigation scenario (RCP2.6), two intermediate scenarios (RCP4.5 and RCP6.0), and one scenario with very high GHG emissions (RCP8.5) (IPCC, 2014). For each category of emissions, an RCP contains a set of starting values and the estimated emissions up to 2100, based on assumptions about economic activity, energy sources, population growth, and other socio-economic factors (IPCC, 2014). The four RCPs, RCP2.6, RCP4.5, RCP6, and RCP8.5, are named after a possible range of radiative forcing values in the year 2100 relative to pre-industrial values (+2.6, +4.5, +6.0, and +8.5 W/m2, respectively).

The IPCC has approved and recommended a number of climate change models, which are a mathematical representation of the interaction between and within the ocean, land, ice and atmosphere. Table 1 identifies 23 models with one or more scenario for each model for total

Table 1
List of climate models and scenarios used in this project.

Model Name	Institution	Scenarios
ACCESS1.0	Commonwealth Scientific and Industrial Research Organization (CSIRO) and Bureau of Meteorology (BOM)	RCP4.5
BCC-CSM1.1	Beijing Climate Center, China Meteorological Administration	RCP2.6, RCP4.5, RCP6.0, RCP8.5
CanESM2	Canadian Center for Climate Modelling and Analysis	RCP2.6
CCSM4	US National Center for Atmospheric Research	RCP2.6, RCP4.5, RCP6.0, RCP8.5
CESM1 (CAM5)	NFS-DOE-NCAR	RCP2.6, RCP4.5, RCP6.0, RCP8.5
CMCC-CM	Centro Euro-Mediteraneo per I Cambiamenti Climatici	RCP8.O
CNRM-CM5	Centre National de Recherches Meteorologiques and Centre Europeen de Recherche et Formation Avancees en Calcul Scientifique.	RCP4.5
CSIRO-Mk3.6.0	Queensland Climate Change Centre of Excellence and Commonwealth Scientific and Industrial Research Organization	RCP2.6, RCP4.5, RCP6.0, RCP8.5
EC-EARTH	Europe	RCP2.6
FGOALS-g2	LASG (Institute of Atmospheric Physics)-CESS (Tsinghua University)	RCP2.6
FIO-ESM v1.0	The First Institute of Oceanography, State Oceanic Administration, China	RCP2.6, RCP4.5, RCP6.0, RCP8.5
GFDL-CM3	NOAA Geophysical Fluid Dynamics Laboratory	RCP6.0
GFDL-ESM2M	NOAA Geophysical Fluid Dynamics Laboratory	RCP2.6, RCP4.5, RCP6.0, RCP8.O
GISS-E2-R	NASA Goddard Institute for Space Studies USA	RCP2.6, RCP4.5, RCP6.0, RCP8.5
HadGEM2-AO	National Institute of Meteorological Research/Korea Meteorological Administration	RCP6.0
HadGEM2-ES	UK Met Office Hadley Centre	RCP2.6, RCP4.5, RCP6.0, RCP8.5
INM-CM4	Russian Institute for Numerical Mathematics	RCP4.5
IPSL-CM5A-LR	Institut Pierre Simon Leplace	RCP6.0
IPSL-CM5A-MR	Institut Pierre Simon Leplace	RCP2.6, RCP4.5, RCP6.0, RCP8.5
MICROC5	University of Tokyo, National Institute for Environmental Studies, and Japan Agency for Marine Earth Science and Technology	RCP2.6, RCP4.5, RCP6.0, RCP8.5
MPI-ESM-MR	Max Planck Institute for Meteorology	RCP8.5
MRI-CGCM3	Meteorological Research Institute	RCP8.5
NorESM1-M	Norwegian Climate Centre	RCP2.6, RCP4.5, RCP6.0, RCP8.5

of 56 model scenarios, a part of a suite of climate models approved by the IPCC. Even though all models can predict the same climate change scenarios, each model delivers significant differences. Assumptions and other model differences produce distinct projections even for the same RCP scenario. As a result, using a larger sample size of models and scenarios will provide a larger range of possibilities. All previous studies have used a small number of models and scenarios, with the majority only using one model with multiple scenarios. These models were selected based on the accuracy analysis of the models and the data availability (IPCC, 2014).

2.2. Baseline and projected climate data

The baseline climate data is defined as the current weather sequence averaged over a number of years. The World Meteorological Organization (WMO) recommends using an averaging period of 30 years to define the current climate baseline (Belcher, Hacker, & Powell, 2005). The climate data projections provide monthly projections from the year 1950 to 2100. This study uses a baseline period of 1970–1999. The model simulations from this period provide the baseline data for predicting the future scenarios. The projected change in climate variable is the difference between the simulated future climate scenario and the simulated base scenario (Belcher et al., 2005).

The projected years from 2011 to 2099 are broken up into three time periods of 30 years: 2011–2039, 2040–2069, and 2070–2099. These three time periods are referred to as Period 1, Period 2 and Period 3, respectively. Monthly data is averaged for each of these three future periods and compared to the baseline average in order to calculate the projected change in climate variable. These changes are then applied to the morphing algorithm (Olonscheck et al., 2011) that will generate hourly weather data. This results in three climate profiles for each model scenario representing the three time periods until the year 2100.

2.3. Scenario analysis

This study predicts 56 model scenarios. The produced weather profiles are separated into their individual RCP scenario. Each RCP scenario contains 14 model profiles as shown in Table 1. A statistical analysis is conducted to illustrate major differences between models within the same scenario group. Using 56 model scenarios adds an extra level of rigor but also sophistication to an analysis. The study thus tries to find a set of 4 reference models that can provide a similar range of climate change effects to the 56 model scenarios. This is carried out by analyzing the 56 projected hourly profiles for 7 representative climate zones in the US as defined by the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE). All cities in the lower 48 states are classified in climate zones 1–7 so the study encompasses a very large area and thus large applicability of the identified climate models.

3. Analysis of projected climate data

The 56 model scenarios were first grouped into their respective RCP groups. For each group, an average, standard deviation and range of cooling degree day (CDD) was calculated. The cooling degree days (CDD) and heating degree days (HDD) are calculated hourly over a year using Eqs. (1) and (2):

$$CDD = \sum^{365} \sum^{24} (T_o - T_b)^+/24 \quad (1)$$

$$HDD = \sum^{365} \sum^{24} (T_b - T_o)^+/24 \quad (2)$$

where T_b is the balance point temperature at which the building does not require heating or cooling (common values of 10 °C and 18 °C were used here for calculating CDD and HDD, respectively); and T_o is the outdoor hourly temperature. The plus sign shows that only positive values will be used. CDDs relate a temperature profile to energy demand, therefore this unit was used in estimating the effects of changing temperature due to climate change on building energy demand without using energy modeling software. This study analyzed all 7 climate zones and 3 time periods. A similar trend was found for all 7climate zones. In order to illustrate the findings, results for Ann Arbor Michigan are presented here. This location was chosen because it is the site of the campus wide energy analysis to be presented later.

The distribution of calculated CDD for all 56 model scenarios differs with time period. As time goes by, the RCPs create a wider distribution of possible climate change outcomes. 3 histograms in Fig. 1 show how the distribution of models expands over time. The distribution of Period 1 resembles a normal distribution. It is a much tighter distribution. The

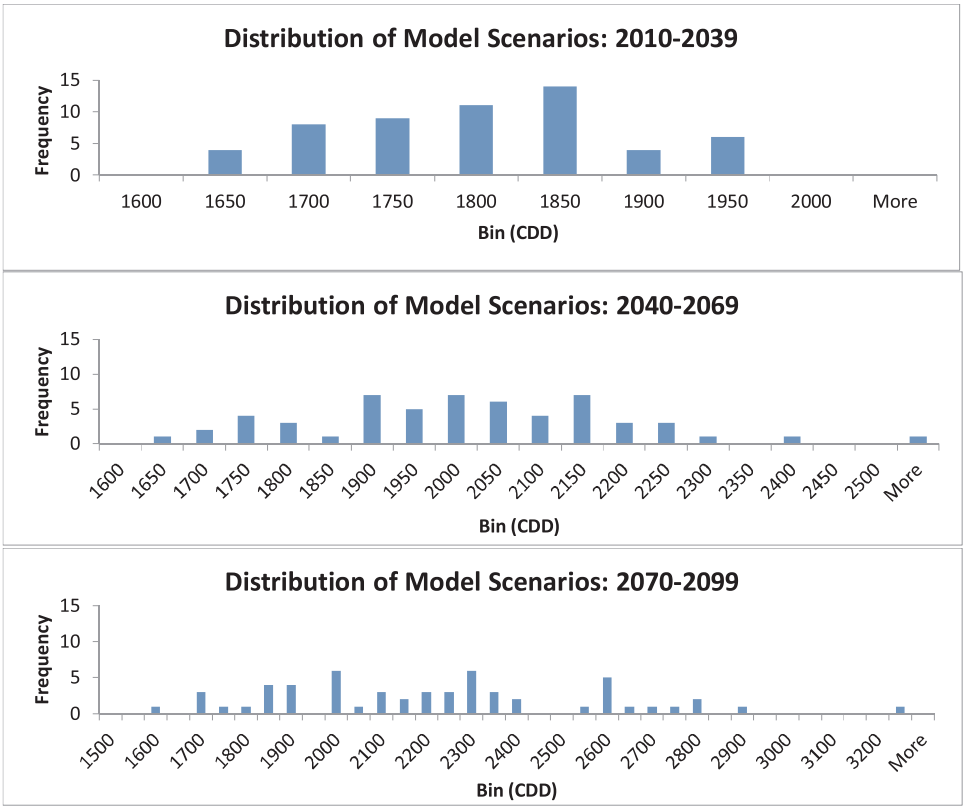

Fig. 1. Histograms representing CDD predictions by 56 models for 2010–2099.

Table 2
Calculated average CDD for Ann Arbor.

RCP Scenario	2.6	4.5	6	8.5
Period 1	1773.10	1775.21	1762.78	1795.05
Period 2	1873.83	1984.27	1951.80	2146.98
Period 3	1847.22	2106.45	2233.52	2605.25

Table 3
CDD standard deviation for Ann Arbor.

RCP Scenario	2.6	4.5	6	8.5
Period 1	96.18	105.76	76.13	79.22
Period 2	145.66	174.74	123.59	174.74
Period 3	158.39	236.47	211.57	276.51

Table 4
CDD range for Ann Arbor.

RCP Scenario	2.6	4.5	6	8.5
Period 1	334.35	346.31	256.84	266.68
Period 2	485.59	568.34	389.57	619.54
Period 3	541.47	798.02	742.12	981.55

distribution in Period 2 and 3 begins to widen. An average CDD for each RCP scenario at each time period was calculated as shown in Table 2. For reference the CDD from the existing the typical meteorological year (TMY) data was calculated to be 1497.425. The trend in CDD is developed as expected. As the RCP and time period increase, the CDD value increases. The standard deviation and range values of projected CDD are presented in Tables 3 and 4. Both the standard deviation and range values increase with time. Period 3 from 2070 to 2099 shows much higher values for all RCP scenarios.

The range of the predicted CDD is the most telling variable. It is observed that the ranges within the same RCP scenario and the same time period are significant. For instance, for the RCP8.5 scenario, the range of the calculated CDD is 981.55 for Period 3 (from Table 4). The calculated average CDD for this scenario and this period is 2605.25 (from Table 2). This indicates the predicted range (uncertainty) of CDD is about 38% from the 56 models. Therefore, if using the weather files generated from the minimum and maximum model that created this range, the building energy simulation model will surely predict a large difference in building energy consumption.

4. Development of reference climate models

For application convenience, four reference climate models were identified to fully encompass the range of all 56 model scenarios. These four identified reference models act like the 12.5%, 87.5% and median models, with the high one covering the top 12.5% of the range, the low one covering the bottom 12.5%, while the other two covering the median 75% of the predicted range (as illustrated in Fig. 2). To ensure that the reference models hold true for all cities and time periods, 21 hourly profile scenarios were used representing 3 time periods and 7 climate zones. For each of the 21 scenarios, the CDD for each of the 56 models were sorted from low to high. Sorted distribution for each model scenario was created and the 4 reference model scenarios were then identified. The 4 model scenarios selected represent a low, low-mid, mid-high, and a high scenario. Each RCP scenario is also represented. The final chosen models and scenarios are:

- Lower Bound Model and Scenario: fio-esm.1.rcp26 by The First Institute of Oceanography, SOA, China;
- Middle Bound Model and Scenarios: cesm4.1rcp45 and ccsm4.1.rcp60 by National Center for Atmospheric Research, USA;
- Upper Bound Model and Scenario: hadgem2-es.1.rcp85 by Met Office Hadley Centre, UK.

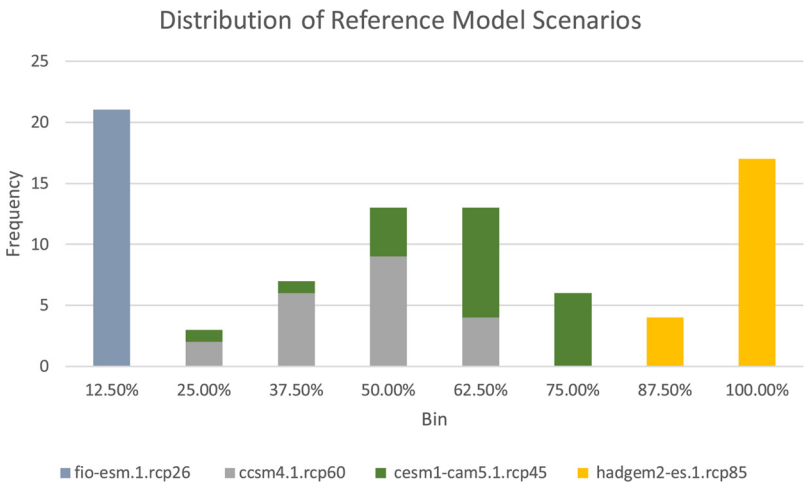

Fig. 2. Histogram distribution of representative models.

A histogram shown in Fig. 2 displays the chosen model scenarios and their sorted distributions when compared to the 56 other model scenarios.

The bin percentage is used to graphically represent the distribution. For example, the 12.5% bin means that when the model scenario is sorted by low-high value, it is located at the bottom 12.5% of the 56 models. Each model scenario has 21 hourly profiles so each model has a total frequency of 21. Fig. 2 shows that the fio-esm.1rp2.6 model scenario best represents the lower bound by falling in the bottom 12.5% for all 21 scenarios. The two middle models fall within the 25%–75% bin, accurately representing the middle bounds with the model scenarios. The high model scenario chosen, hadgem2-es.1rcp8.5, is the best fit for the upper bounds of all 56 model scenarios. These 4 models can thus precisely represent the wide range of all 56 models.

In order to validate the accuracy of the four reference models, TMY3 data (1991–2005) for Boulder, Colorado was predicted using the climate model data and TMY2 data (1961–1990). The TMY2 data was used as the base to generate hourly data, as required in the morphing algorithm. The predicted 1991–2005 hourly data upon TMY2 was then compared with TMY3 data to validate both the climate model and the morphing algorithm. Three variables were validated for accuracy: average monthly dry bulb temperature (dbt), monthly maximum temperature and monthly minimum temperature. All three variables are used in the morphing algorithm for dry bulb temperature calculation so their accuracy is critical. Fig. 3 shows a comparison of average monthly dbt. The results show that the accuracy of the predicted TMY3 monthly dbt is within 10% of the actual values. The same outcomes are found for maximum and minimum temperature. Although the majority of data points lie within the 10% error, some points spread outside. Many of the points lying outside the 10% error occur when the dbt, maximum and minimum temperature are between $-5\,^{\circ}C$ and $5\,^{\circ}C$. Since the actual data value is small, a small deviation will produce a large percent error. Overall, the climate model data and the Morphing Algorithm provide an accurate prediction of climate variables.

5. Impacts of climate changes on building stocks

5.1. Campus model

It is more important to understand the impacts of climate change on building energy use at a large scale (e.g., district, city, or even region) than individual buildings. Predicting building energy use at a city level is a complicated process, and few approaches are available. Lim (2016) proposed a probabilistic based stochastic deterministic coupled method to estimate the distribution of building energy consumption at a large scale. The proposed methodology was applied here to a campus scale (University of Michigan - UM) as a demonstration.

According to the campus wide analysis of energy use and building characteristics, it was determined that energy use intensity (EUI) differs greatly by building type. The 75 UM buildings were thus classified into 5 representative buildings, based on function and EUI: laboratory, clinic, service building, campus building, and residential building. EnergyPlus, a widely used building energy simulation tool, was employed to create five models for these representative buildings. The calibrated EnergyPlus models were used to estimate the implications of climate change on a campus wide basis. The metrics analyzed include: total change in campus energy consumption, changes in heating and cooling energy, and changes in peak electricity demand. Twelve future weather files were created from the 4 reference climate models and 3 time periods. Each future weather file represents an average hourly weather profile for the corresponding period in Ann Arbor, Michigan. The weather files were then applied to the 5 representative building energy models.

5.2. Impacts on building energy consumption

The 12 climate projected weather files were utilized for each of the 5 UM representative buildings. For each projected scenario, a new EUI was calculated for representative buildings and then aggregated across the campus by associated floor areas. A summary of these results can be seen in Fig. 4. The results directly correlate to the climate analysis results. The low model shows an initial increase in campus energy use, but begins to decline slowly. This is due to the declining CO_2 concentration associated with the RCP2.6 group. IPCC predicted the future changes in atmospheric CO2 and surface temperature, in which RCP2.6 displays a unique trend. Right around the year 2050, a decline is observed in both atmospheric CO_2 and surface temperature for the RCP2.6 scenario (IPCC, 2014). The other three models show a steady increase in total campus energy use. This means that the energy use associated with the increasing CDD outweighs the energy use associated with the decreasing HDD.

A closer look into the heating and cooling energy reaffirms this. Fig. 5 shows the percent increase in campus cooling energy. The difference between the high and low model is substantial, with the major difference between RCP2.6 and RCP8.5. Cooling energy will likely increase, ranging from 5% to 90%. This is dependent on what RCP scenario the future holds. Increasing temperatures also result in a decrease in heating energy. However, the decrease in heating energy is much lower than the increase in cooling energy, although the changes in HDD and CDD are almost equal and opposite. When combining the total heating and cooling energy, the increase in cooling energy becomes dominant. The total HVAC energy increases from 2% to 40%. These

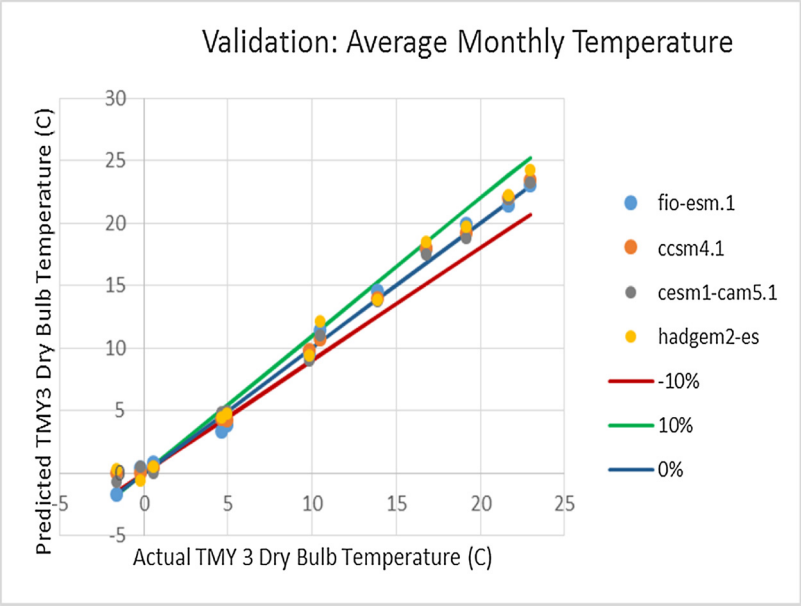

Fig. 3. Validation of average monthly dbt.

results do not include the increase and decrease in fans and pump energy, which however were included when calculating the total campus energy in Fig. 3.

5.3. Implications to utility

Results from climate change impact study on building stock can be extremely important for local utilities. Energy demanded by a particular building stock is often directly supplied from a utility, therefore any predicted changes in the energy demand can be used by the utility to adapt in advance. For the UM, the cooling energy is predicted to increase. This implies that the utility must be able to provide extra electricity to the campus in future decades. Fig. 6 projects the additional annual cooling power required for each time period and climate model. In a wide range, but all show an increase in cooling power.

In reality, the power to the UM campus is supplied by a few sources. The main source is the UM natural gas fired power plant. The capacity of the power plant is 40.5 MW. On average the plant supplies about 150,000 MW h of electric power annually. If averaging the 4 model scenarios for each time period, there is an average increase, respectively, of 11,800 MW h, 20,775 MWh, and 31,939 MW h annually for period 1 through 3. The increase in additional cooling energy makes up 8%, 14% and 21% of the total annual production from the power plant. This additional energy demand could be high enough for the utility to have to build a new power plant. In the worst case scenario – RCP8.5, the additional cooling energy demand is 68,800 MW h. This makes up almost 46% of the total power plant annual production, which is alarming for the utility.

For a utility, another very important measure of electricity distribution is peak demand. Peak demand tends to increase in the hot summer months. With temperature likely to increase, the peak demand will also increase. Each representative building on the UM campus clearly shows the general increase in peak demand, as revealed in Fig. 7 for Period 3. The Residence building presents the greatest increase. The Lab shows the smallest increase in peak demand. Overall, there is a wide variety of change for each building, and the peak demand

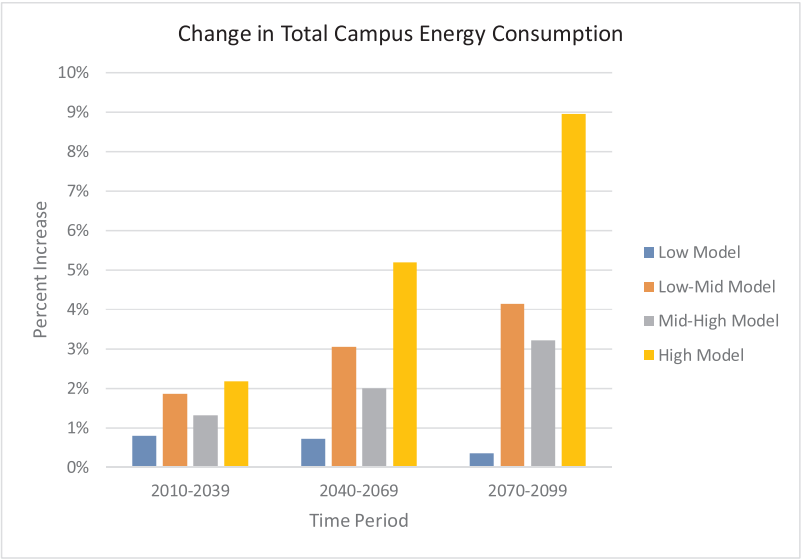

Fig. 4. Summary of predicted changes in campus energy consumption.

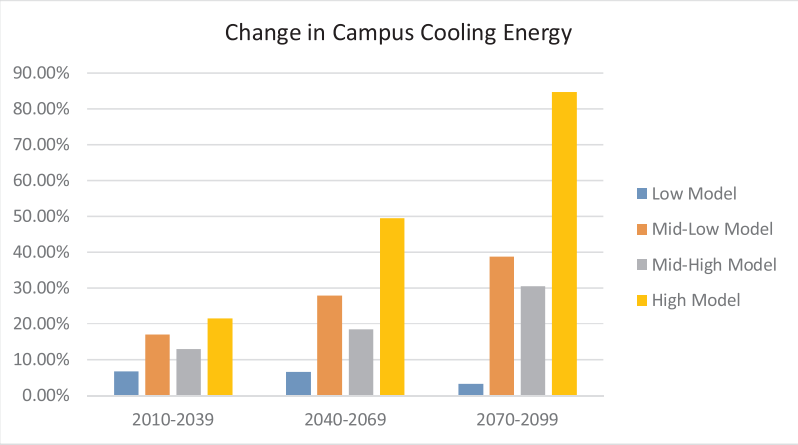

Fig. 5. Summary of predicted changes in campus cooling energy.

increases with time as temperature increases. For a utility this means that it will need to provide more peaking power or will use its peaking units more often, which will cost more money. It may also imply they may have to build more peaking plants if necessary to meet the change in peak demand. Early prediction of how energy consumption could change can give utilities insight into how they need to prepare for the future. It will allow them more time to prepare and ultimately could save them a lot of money.

5.4. Implications to economics

The predicted changes in energy ultimately lead to changes in energy costs. Based on the cooling energy data from the base representative models of the UM, with an average price of electricity for the state of Michigan of 13 cents per kWh, the UM spends about $9.7 million USD on cooling energy annually (EIA, 2015). Note that this does not include demand charges. Fig. 8 shows the annual increase in cooling costs for each climate model and time period.

Under all scenarios an increase in cooling cost is confirmative. The low model scenario predicts a very small increase of less than $1 million USD, which may not be worrisome for the UM. However, the higher scenarios present a much larger increase in cooling cost. The high model shows an increase of over $8 million USD annually, an 85% increase. Improvements to the campus cooling systems may need be considered to reduce the future cooling costs.

Although the campus cooling energy increases, the campus heating energy is the opposite. For all 4 climate models a decrease in heating cost is observed as expected. The magnitude of the savings is much smaller than the magnitude of increased cooling cost. This is because of the price disparity between electricity and natural gas. At $0.12/kWh, the price of electricity converts to about $33/GJ. The price of natural gas is significantly lower at just $2.59 for the Mid-Western US (EIA, 2015). Hence, the additional HVAC costs due to climate change are heavily dominated by the increase in cooling energy.

6. Implications of climate change to building energy policies and standards

Prediction of how climate change will affect building stocks can provide quantitative insight to how a city and local authority will need to adapt. Building codes and standards should take the prediction of climate change into consideration. ASHRAE bases building envelope and system standards on climate zone so as to optimize building performance. This study demonstrates that in the near future climate zones may change. Buildings being built for one climate zone (and code) may under preform in future decades. Possible changes in climate and results from studies such as this one, should be taken into consideration when building standards are renewed. The changing of climate zones also presents an interesting new design for climate change. For standard makers, presenting the effects of climate change on changes in dry bulb temperature or degree days could prove to be less effective because the standards are based on climate zones.

Presenting the effects of climate change through changing climate zones could be an effective alternative in influencing standard makers within the building and construction industries. Changes in climate zones provide a larger perspective on climate change as well. Areas that

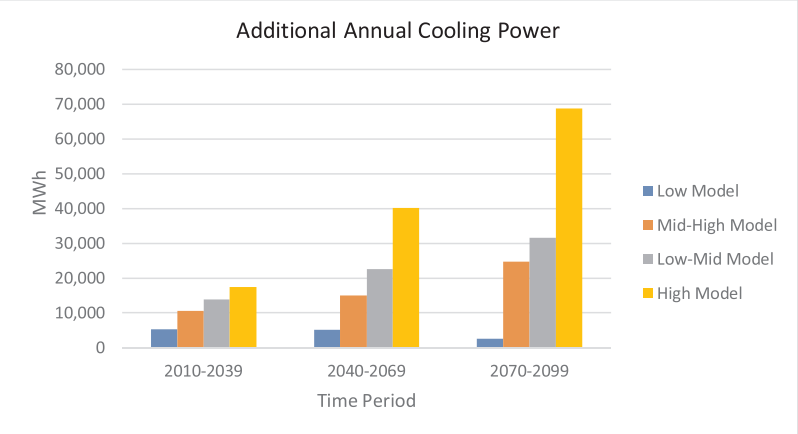

Fig. 6. Utility to provide additional annual cooling power.

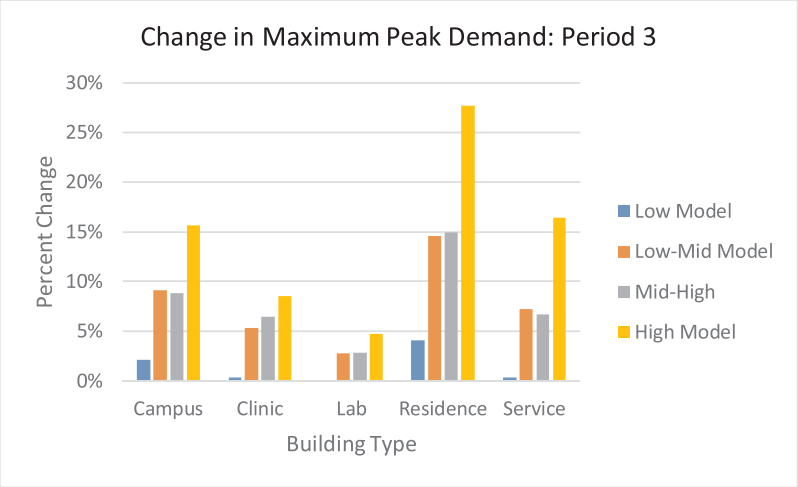

Fig. 7. Predicted changes in electricity peak demand for 2070–2099.

are the most affected by climate change can see their climate zone changed by as many as 2 zones. Other areas may only see changes in 0 or 1 zone. Therefore, this can act as a vulnerability metric, which is also extremely useful. As a demonstration, a climate zone study was performed for each of the 7 representative cities for climate zones 1–7. Using the 4 reference climate model profiles, degree days were calculated to determine the new climate zone. Results are presented in Table 5. The colors represent the changes in climate zone for each time period and model. Green represents no change, yellow represents a change of 1 climate zone, and red represents a change of 2 climate zones. Analysis such as this can provide a visible and more tangible metric for climate change impact.

7. Discussions and conclusions

When applying climate models to project future climate change scenarios, a limited number of models were often used. Analysis of 56 newest model scenarios approved from the IPCC revealed that the range of model projections varies significantly. Within each RCP scenario, results from a simple degree day analysis indicate that this range can have a large impact on the predicted energy consumption of building stock. Four representative climate models were identified for application convenience that can cover the full range of the predictions of the 56 model scenarios. The four models selected were: FIO-ESM v1.0 (Low), CESM1-CAM5 (Middle), CCSM4 (Middle), and HadGEM2-ES (High).

The case study for a campus building stock energy prediction using the future weather files from the four representative models reveals a wide range of possible changes in energy consumption. The low model shows a less than 1% increase in total campus energy for all periods, while the high model shows an increase of 2%, 5%, and 9% for period 1, 2, and 3, respectively. The increase in campus energy consumption is due to the large increase in campus cooling energy. When averaged over 3 periods, the cooling energy increases 5%, 28%, 20% and 52%, respectively, for the low, low-mid, mid-high, and high models. Although the campus heating energy decreases, it is not enough to offset the larger increase in cooling energy, resulting in an increase in total HVAC energy.

Averaging the four model scenarios for each time period yields an average increase of 11,800 MW h, 20,775 MWh, and 31,939 MW h annual electricity, respectively, for period 1 through 3. When compared to the local power plant generation, these increases make up 8%, 14% and 21% of the total annual generation. Furthermore, the peak demand is expected to increase by as much as 27%. Early prediction on energy consumption change will give utilities insight into how they need to prepare for the future. It will provide them more time to prepare and ultimately could save them money.

Using the results of the degree day analysis, a climate zone analysis can be performed. Projecting changes in climate zones for a specific location could be a useful metric in presenting and visualizing the

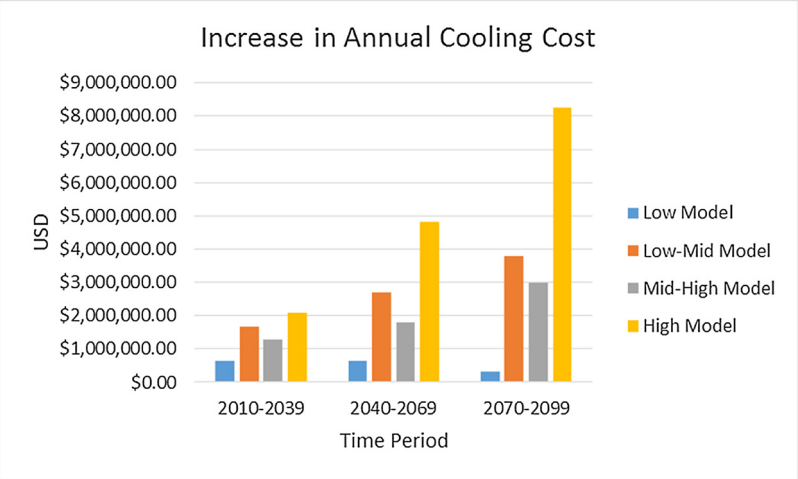

Fig. 8. Projected increase in UM cooling energy cost.

Table 5
Changes in climate zones predicted by four reference climate models (1–7 are climate zones as defined by ASHRAE; colors represent the changes in climate zone: green = no change, yellow = change of 1 climate zone, red = change of 2 climate zones).

Miami: Zone 1	**Low**	**Low-Mid**	**Mid-High**	**High**
Period 1: 2010-2039	1	1	1	1
Period 2: 2040-2069	1	1	1	1
Period 3: 2070-2099	1	1	1	1
Phoenix: Zone 2	**Low**	**Low-Mid**	**Mid-High**	**High**
Period 1: 2010-2039	1	1	1	1
Period 2: 2040-2069	1	1	1	1
Period 3: 2070-2099	1	1	1	1
Las Vegas: Zone 3	**Low**	**Low-Mid**	**Mid-High**	**High**
Period 1: 2010-2039	2	2	2	2
Period 2: 2040-2069	2	2	2	1
Period 3: 2070-2099	2	2	2	1
Albuquerque: Zone 4	**Low**	**Low-Mid**	**Mid-High**	**High**
Period 1: 2010-2039	4	3	3	3
Period 2: 2040-2069	4	3	3	3
Period 3: 2070-2099	4	3	3	2
Boulder: Zone 5	**Low**	**Low-Mid**	**Mid-High**	**High**
Period 1: 2010-2039	5	5	5	4
Period 2: 2040-2069	5	4	4	3
Period 3: 2070-2099	5	4	4	3
Helena: Zone 6	**Low**	**Low-Mid**	**Mid-High**	**High**
Period 1: 2010-2039	6	5	5	5
Period 2: 2040-2069	6	5	5	5
Period 3: 2070-2099	6	5	5	4
Duluth: Zone 7	**Low**	**Low-Mid**	**Mid-High**	**High**
Period 1: 2010-2039	7	6	6	6
Period 2: 2040-2069	7	6	6	5
Period 3: 2070-2099	7	5	6	5

effects of climate change. This provides important information for standard and policy developers to consider the future code and policy revisions and refinements.

The study approach presented in this paper can help local decision makers and local utilities make more informed decisions regarding future policies and business choices. The same process can be applied to other locations in the U.S. and throughout the world, which can help in making worldwide decisions regarding building standards, energy generation, energy management, and emission policies.

Acknowledgement

The first author gratefully acknowledges the funding from USAID through the SHERA program - Centre for Development of Sustainable Region (CDSR).

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